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A framework for assessment of Technological Readiness Level (TRL) and Commercial Readiness Index (CRI) of asset end-of-life strategies

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ABSTRACT: A substantial number of industrial assets within the manufacturing, power generation, transportation, oil and gas, petrochemical processing, mining and construction sectors are facing operation beyond their anticipated design life and will be in need of intensive maintenance services in the coming years. At the end of an asset's design lifetime, the operators must make a decision on either rejuvenating the components through life-extension solutions or decommissioning the asset. This means that life extension policies (e.g. remanufacturing, reconditioning, repurpose, retrofitting) and decommissioning strategies (e.g. recycling and disposal) will continue to play a crucial role in the future management of industrial assets. However, some of the End-of-Life Management Strategies (ELMS) or their emerging technologies may not be mature yet, and therefore application of such strategies can cause extensive uncertainties. A well-documented Technological Readiness Level (TRL) and Commercial Readiness Index (CRI) for these strategies and related technologies will be a key in reducing the uncertainties involved in implementing ELMS in various industries. This paper aims to propose a systematic framework consisting of six different processes to help asset managers evaluate the TRL and CRI of different ELMS and their corresponding technologies. An essential part of developing this framework is the strong collaboration among academics and industrial experts with several years of experience in undertaking life extension and decommissioning projects. For purpose of illustrating the model, a case study involving end-of-life strategies of wind turbines is provided and the results are further discussed. The data required for this study is collected from various sources, including the published literature and industrial reports as well as by surveying academic and industrial experts. The results of this study indicate that TRL and CRI assessments are not only an effective means of evaluating the technological status of different ELMS but also a means for risk management decision making.

1 INTRODUCTION

Over the past several decades, asset owners in the manufacturing, power generation, transportation, oil and gas, petrochemical processing, mining and construction industries have focused on optimizing the design of their systems, enhancing installation techniques and improving production. However, in recent years, many of the assets operating in the above-mentioned industries are entering a new phase of development where assets are expected to reach their anticipated design lifetime. Hence, the attention of industries is now shifting towards how these ageing assets can be managed, to ensure that they continue to deliver high level of service beyond their original design lifetime.

The two most popular end-of-life management strategies (ELMS) include asset life extension and decommissioning. Asset life extension involves the application of technical and administrative procedures to extend the useful life of engineering structures, systems and components at the end of their design lives, provided they are technically and economically qualified. The benefits of extending the service life of ageing assets are enormous. For instance, extending the service life of a multi-million pound system could result in substantial return on investment. It also has the tendency to increase production volume and reduce CO_2 emissions due to slow down in the manufacturing of new products.

On the other side, decommissioning represents the last stage of the asset life cycle. It involves the total or partial removal of assets, which ensures the restoration of a site (land or seabed) to suitable condition for other uses and also maximizes material recovery from removed assets through waste management. Despite the huge potential of life extension and decommissioning to asset owners, the life extension policies and decommissioning strategies as well as their emerging technologies are not yet matured. Therefore, the application of these ELMS in many sectors often result in huge technological and commercial uncertainties.

In order to minimize the technological and commercial uncertainties involved in implement-

ing ELMS in various industries, it is important for asset owners to explore, assess and evaluate the maturity level of life extension policies and decommissioning strategies for different systems and components, taking into account technological readiness level (TRL) and commercial readiness index (CRI) of related technologies.

The TRL was first developed by NASA in 1974 as a benchmarking tool to assess and communicate the maturity levels of new technologies (Mankins, 2009). Since then, it has been applied in various industries to provide a measurement of technology maturity. Although the TRL concept is appropriate to help minimize technological uncertainties, there are often commercial or financial uncertainties characterising new programmes and technologies entering the market. Another accepted process that can be used for benchmarking the commercial maturity of new technologies is the commercial readiness index (CRI). The CRI was developed by the Australian Renewable Energy Agency (ARENA) to evaluate the commercial readiness level of renewable energy technologies.

Understanding and communicating the TRL and CRI for life extension policies and decommissioning strategies as well as their related technologies will not only enable asset owners to reduce the uncertainties involved in implementing ELMS in various industries but also can help them to determine how key assets could be competitive beyond their original design life.

The aim of this paper is to propose a framework to evaluate the maturity level of different life extension policies and decommissioning strategies by taking into account the TRL and CRI of related technologies. The proposed framework is tested with a case study involving offshore wind turbine blades that have reached the end of their original design lives. Our results indicate that the proposed framework provides a powerful decision-making tool to support asset owners to efficiently manage engineering structures, systems and components when they reach the end of their original design life.

The rest of the paper is organized as follows. Section 2 presents the conceptual framework and the steps required to aid in assessing the maturity levels of life extension policies, decommissioning strategies and the related technologies. In Section 3, the model is applied to a case study involving wind turbine blades and the results are analyzed in Section 4. Finally, the conclusions and future research directions are outlined in Section 5.

2 THE PROPOSED FRAMEWORK

The proposed framework for evaluating the maturity level of life extension policies, decommission strategies and emerging technologies is shown in Figure 1, which includes five steps. These steps are explained in details as follows:

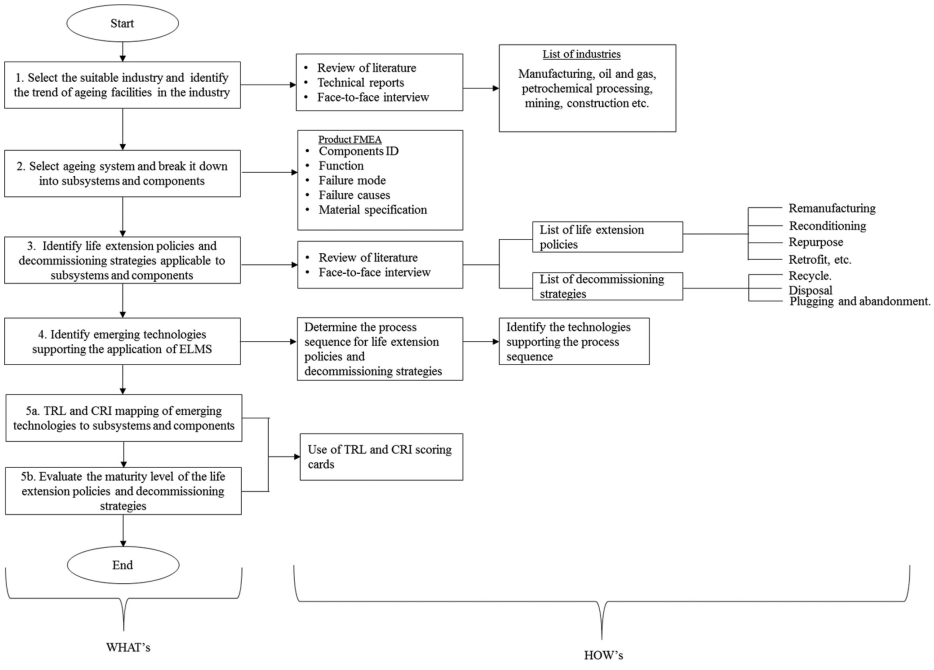
Start
1. Select the suitable industry and identify the trend of ageing facilities in the industry
Review of literature
Technical reports
Face-to-face interview
List of industries
Manufacturing, oil and gas, petrochemical processing, mining, construction etc.
2. Select ageing system and break it down into subsystems and components
Product FMEA
Components ID
Function
Failure mode
Failure causes
Material specification
3. Identify life extension policies and decommissioning strategies applicable to subsystems and components
Review of literature
Face-to-face interview
List of life extension policies
Remanufacturing
Reconditioning
Repurpose
Retrofit, etc.
List of decommissioning strategies
Recycle.
Disposal
Plugging and abandonment.
4. Identify emerging technologies supporting the application of ELMS
Determine the process sequence for life extension policies and decommissioning strategies
Identify the technologies supporting the process sequence
5a. TRL and CRI mapping of emerging technologies to subsystems and components
Use of TRL and CRI scoring cards
5b. Evaluate the maturity level of the life extension policies and decommissioning strategies
End
WHAT's
HOW's

Figure 1. Steps for applying the proposed framework.

Step 1. Select the suitable industry and identify the trend of ageing facilities: As the purpose of this study is to evaluate the maturity level of different life extension and decommissioning policies as well as their related technologies to support end-of-life management of structures, systems and components within different industries, it is key to investigate the trends in the number of facilities approaching, have reached or exceeded the end of their original design life within a specific industry or company. This task can be achieved by reviewing journal articles, conference papers, technical reports, company's dossier and face-to-face interview with industrial experts. The industries/companies that can apply the proposed framework to support end of life management of ageing assets include (but not limited to) the following: power generating (nuclear energy, renewable energy and power transmission and distributions), manufacturing, transportation, oil and gas, petrochemical processing, mining, construction, etc.

Step 2. Select an ageing facility and break it down into subsystems and components: In this stage, an ageing facility is selected and decomposed into manageable units. Decomposition of ageing facility into manageable units is to facilitate the mapping of applicable life extension policies or decommissioning strategies for high-risk subsystems and components of the facility. The task of breaking down a facility into manageable units can be achieved through the use of product failure mode and effect analysis (FMEA).

Step 3. Map applicable life extension policies and decommissioning strategies to subsystems and components: At this stage, all applicable life extension policies and decommissioning strategies are identified and mapped to critical subsystems and components of the facility. The life extension policies and decommissioning strategies can be identified though literature review as well as consultations with industry experts. Examples of life extension policies include remanufacturing, reconditioning, repurpose, retrofitting, etc. while recycling, disposal and plugging and abandonment are examples of decommissioning strategies. For more comprehensive description of different life extension policies, readers can refer to Shafiee and Animah (2017).

Step 4. Identify emerging technologies for implementing life extension policies and decommissioning strategies: The goal of this stage is to identify the technologies related to the implementation of the applicable life extension policies and decommissioning strategies for the critical subsystems and components. In order to identify the related technologies, one must understand the process sequence for each life extension policy or decommissioning strategy. Understanding the process sequence for different life extension policies and decommissioning strategies will help in identifying the appropriate technologies and their features and provide specific information that allows for the allocation of TRL and CRI respectively.

The process sequences involved in extending the useful life of an engineering structure, system or component include cleaning, disassembling and inspection, repair, reassembling and testing. Whereas cutting, lifting, removal and material recovery/disposal may constitute decommissioning process sequences for systems and components, especially within the offshore oil and gas and offshore wind power industries.

Step 5. Evaluate the maturity level of the life extension policies and decommissioning strategies: This task of the proposed framework is performed by utilizing the TRL and CRI assessment scales, shown in Figure 2. The TRL scale helps to assess the technical maturity of the life extension policies and decommissioning strategies as well as their related technologies whereas the CRI scale assists in evaluating the commercial readiness of the strategies and the related technologies.

There are two rounds of activities at this stage. In the first activity, the TRL and CRI of the emerging technologies supporting the implementation of life extension policies and decommissioning strategies for subsystems and components are determined using Eq. (1) and (3) below:

$$TRL_i = \sum_{j=1}^{n} w_{ij} TRL_{ij} \tag{1}$$

$$\sum_{j=1}^{n} w_{ij} = 1; for \forall_i \tag{2}$$

where w_{ij} is the relative importance (weight) of technology j for policy/strategy i, and

$$CRI_i = \sum_{j=1}^{n} v_{ij} CRI_{ij} \tag{3}$$

$$\sum_{j=1}^{n} v_{ij} = 1; for \forall_i \tag{4}$$

where v_{ij} is the relative importance (weight) of technology j for the policy/strategy i. The weights w_{ij} and v_{ij} can be allocated by experts or estimated

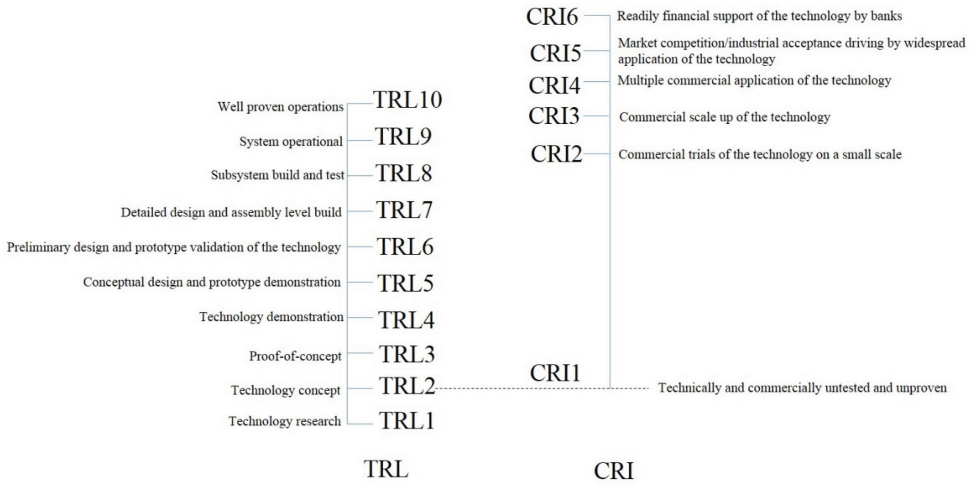

Figure 2. Technology readiness level (TRL) and commercial readiness index (CRI) scale (ARENA, 2014 and Straub, 2015).

using the Delphi-analytical hierarchy process. The second activity involves evaluating the maturity level of each life extension policy and decommissioning strategy (M) using Eq. (5):

$$M = \sum \alpha TRL_i + (1-\alpha)CRI_i, 0 < \alpha < 1 \quad (5)$$

where α and $1-\alpha$ represent the relative importance (weight) of TRL and CRI in relation to each other.

3 APPLICATION TO WIND TURBINE BLADES

The number of wind turbines reaching the end of their original design life of 20–25 years has been increasing in recent years, hence repowering, life extension and decommissioning activities are attracting the attention of both practitioners and scholars in the wind power industry. In order to illustrate the efficacy of the proposed framework, it is applied to offshore wind turbine blades which have reached the end of their original design lifetime. The data used in this study was collected from literature, academics with expertise in wind energy industry as well as blade manufacturers. In this Section, the results of the application case are presented and discussed.

Step 1. The wind power industry is the focus of this case study.

Step 2. From the product FMEA of the wind turbine provided by the operator, the proposed framework is applied to the blades, which are made of composites.

Step 3. The life extension policies and decommissioning strategies considered for the blades are briefly explained below.

- Remanufacturing: It involves the use of modern technologies and procedures to break assets down into core parts, and then engineering changes are made to the core parts in order to meet Original Equipment Manufacturers (OEM) specifications and performance. In most cases, the cost of a remanufactured system is less than that of a brand new system but with an equivalent warranty to that of a brand new system (Animah *et al.*, 2017).
- Reconditioning: According to Shafiee and Animah (2017) reconditioning involves taking appropriate actions to restore a defective system to between "as good as new (AGAN)" and "as bad as old (ABAO)" condition, hence the output is less than that of OEM's stated output.
- Repurpose: It involves taking the necessary steps to create a new use or purpose for an existing system which was originally designed for a different purpose (Aguirre, 2010; Coughlan *et al.*, 2015). With this life extension policy, engineering actions and processes are applied to make transformation to key parts of a system. The transformation is based on the technical feasibility of the engineering processes, environmental performance and economic viability of the system for future operations (Bauer *et al.*, 2017).
- Retrofitting: It involves the process of replacing old components of a system with modern

Table 1. Overview of technologies used to support remanufacturing, reconditioning, repurpose and retrofitting process for blades.

Process sequence	Technologies	Technology features
Cleaning	Jet cleaning (water jet, abrasive (sand) blasting cleaning, dry ice cleaning etc.).	With this technology, rust, grease, oil and other contaminants are removed from surfaces of components through physical interaction of the accelerated medium (sand, water, dry ice etc.) by compressed air or high pressured water (Liu et al., 2013).
	Organic solvent cleaning	This method of cleaning is performed by drenching/soaking components in organic solvent or spraying the organic solvent on component surfaces while cleaning takes place as a result of dissolution and chemical reaction (Kikuchi et al., 2011).
	Ultrasonic cleaning	Ultrasonic cleaning involves the use of high frequency (20–400 KHz) sound waves to generate agitation in a liquid (Niemczewski, 2007). The cavitation bubbles produced as a result of the agitation acts on contaminants on the surfaces for cleaning.
Disassembly	Disassembly embedded design	Disassembly embedded design integrates a disassembly mechanism into a system during design, e.g. Snap fits to dislodge locked out of position (Soh et al., 2014).
	Active disassembly	This technique makes use of external triggers such as temperature, magnetic force or pressure, for the release of fasteners. It include utilizing smart materials, freezing elements, soluble elements, pneumo-elements and hydrogen storage alloy elements as a fastening technique (Duflou et al., 2006).
Repair/ Modification/ Retrofitting process	Laser repair technology (LRT)	LRT is suitable for the repair/rebuilding of worn out metallic parts, which are considered non-repairable using traditional welding or plating techniques. The process involves injection of metal powder into a focused beam of a high powered laser in a tightly controlled atmospheric condition.
	Advanced mechanical machining processes	This technology is needed when the repair of existing components require CNC milling, turning, drilling, tapping, cutting and other machining operations.
	Industrial 3D printing	This is an additive manufacturing process which uses high powered laser fusion to produce components by building layer upon layer from a predefined 3D digital design.
	Tubercle technology	This technology mimics the bumps on humpback-whale fins to develop a more efficient wind turbine blades.
	Plastic surgery	This the use of plastic surgery to make old, smaller and less efficient wind turbine blades into bigger and efficient ones without replacing them at the end of life.
Testing	Shearography system	This is the use of optimal measurement technology or shearorgraphy sensor to detect defects such as wrinkles, delaminations, debondings and kissing bondings in wind turbine blades.

Table 2. Overview of technologies used to support recycling and disposal of wind turbine blades.

Process sequence	Technology	Technology features
Material recovery	Pyrolysis	This is the use of pyrolysis recycling technology (i.e. burning of the resin matrix with limited oxygen).
	Mechanical grinding	This is the reduction of composite materials into suitable sizes and grounding them into different grades using mechanical processes such as hammer mill.
	Solvolysis	This technology makes use of physico-chemical separation process for full material recovery of thermosets. The process uses water at sub-supercritical temperature to breakdown thermoset resin, in order to remove it from the fibre.
	Incineration	This is the burning of end of life product for energy generation.
Disposal	Landfill	Burying the materials used in the manufacturing of the system in the ground.

equivalent in order to achieve higher functionality and availability. An example of retrofitting is the blade extension program for wind turbines, in order to increase the swept area of the rotor to increase power generation at low speed.

- Recycle: Complex industrial equipment are made of different materials. In post-decommissioning, scraps from these infrastructure in the form of metals and non-metals are generated, recycling processes are then used to recover high grade materials from these scraps for other uses, thereby limiting the amount of waste generated at the end of life (Yang *et al.*, 2012). However, recycling of the products can reduce the exploitation of natural resources and protect the environment.
- Disposal: Open burning and landfills are examples of the popular disposal options for components and materials from industrial systems. However, the economic value of reusing the system or recovering materials through recycling is lost when this strategy is implemented at the end of original design life.

Step 4. A number of technologies have been proposed by both researchers and practitioners to support the process sequence for implementing life extension policies and decommissioning strategies across different industries. The technologies that can support the process sequence of remanufacturing, reconditioning, repurpose and retrofitting of wind turbine blades are shown in Table 1. On the other hand, Table 2 shows the overview of the related technologies that can support the material recovery/disposal process sequence of recycle and disposal of wind turbine blades.

Step 5. The maturity level of the life extension policies and decommissioning strategies applicable to wind turbine blades using the TRL and CRI scales in Figure 2 is evaluated. The TRL and CRI of each technology was evaluated through experts' elicitation. First, the experts were asked to allocate TRL and CRI to the emerging technologies supporting the implementation of the life extension policies and decommissioning strategies obtained from the literature. Table 3 shows the TRL and CRI of the emerging technologies supporting the implementation of life extension policies and decommissioning strategies for wind turbine blades using Eqs. (1) and (3). The weights assigned to evaluate *TRL* and *CRI* for each technology were achieved through a consensus reached by a panel of experts. Second, the maturity level of each life extension policy and decommissioning strategy has been evaluated using Eq. (5) and are ranked in Table 4.

Table 3. TRL and CRI of emerging technologies supporting the life extension and decommissioning strategies for wind blades.

Emerging technologies	TRL	CRI
Jet cleaning	10	5
Organic solvent cleaning	–	–
Ultrasonic cleaning	–	–
Disassembly embedded design	10	5
Active disassembly	7	1
LRT	5	1
Advanced mechanical machining processes for composites	2	1
Tubercle	7	1
Plastic surgery	7	1
Shearograph	9	2
Industrial 3D printing	2	1
Pyrolysis	3	1
Mechanical machines (grinding, stripping, crushing etc.)	3	1
Solvolysis	3	1
Incineration	9	2
Landfill	10	3

As shown in Table 4, disposal was chosen as the most appropriate ELMS for wind turbine blades. This is because the maturity level of landfill as a technology for disposing the blades made of composites are technically well proven, commercially available and relatively cheap in many parts of the world. The second and third most suitable ELMS for the wind turbine blades are remanufacturing and reconditioning. Retrofitting, repurposing and recycling were identified as the fourth, fifth and sixth preferred ELMS for the blades. This is because the key technologies needed to support the implementation of these ELMS for products made of composite materials are still in the experimental phase. This means that the technologies are not technically matured for large scale commercial applications. For instance, pyrolysis, mechanical

Table 4. Ranking of maturity level of life extension policies and decommissioning strategies for wind turbine blades.

Life extension policies/Decommissioning strategies	Ranking
Disposal	1
Remanufacturing	2
Reconditioning	3
Retrofitting	4
Repurpose	5
Recycle	6

grinding and Solvolysis which are considered as the most suitable recycling technologies for composite products such as wind turbine blades are at the laboratory scale in terms of technological development (Rybicka *et al.*, 2016). Thus, making landfill and incineration the most widely used technologies to support end of life management of wind turbine blades when they reached the end of their original design life.

5 CONCLUSION

In this study, a methodology was proposed to assist in understanding and communicating the maturity level of life extension policies and decommissioning strategies for industrial assets reaching the end of their original design lives. The proposed methodology considered TRL and CRI of emerging technologies supporting the implementation of different life extension policies and decommissioning strategies, in order to rank the best ELMS. To the best of our knowledge, this was the first time the TRL and CRI scales were integrated to communicate the maturity level of different life extension policies and decommissioning strategies for products reaching their end of life. For the purpose of clearly illustrating the efficacy of the proposed framework, it was applied to determine the maturity level of different life extension polices and decommissioning strategies for wind turbine blades. The findings from the case study indicated that disposal of wind turbine blades through landfilling was considered as the most appropriate strategy for managing wind turbine blades when they reached the end of their original design life. This was followed by remanufacturing, reconditioning, retrofitting, repurpose and recycle.

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